THE SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM): A BREAKTHROUGH IN REMOTE SENSING OF TOPOGRAPHY

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ABSTRACT

The Shuttle Radar Topography Mission (SRTM), flown on the Space Shuttle Endeavour on Flight STS-99 and launched on 11 February 2000, will produce digital elevation data of the Earth's land mass between 60 degrees north latitude and 54 degrees south latitude. This data will be at least one order of magnitude more precise in the elevation resolution, and will have postings of 30 m, representing an order of magnitude increase in the density of the postings over currently available data.

INTRODUCTION

Digital topographic information is crucial to scientific investigations in geology, geophysics, hydrologic modeling, and ecology. This type of data also forms the basis for monitoring the surface deformation during earthquakes, inflation of volcanoes, and flood inundation monitoring. In the civil sector, this type of data could be used for urban planning and the design of transportation infrastructure.

Synthetic aperture radar (SAR) interferometry has been shown to be a very cost effective tool for measuring digital topography.[1] The Shuttle Radar Topography Mission (SRTM) acquired data capable of producing a three-dimensional image of 80% of the Earth's land surface in a single 10-day Space Shuttle flight.[2] It is the first spaceborne single-pass interferometric SAR and will produce the first near-global, high-resolution, digital elevation map. Such a global map will be constructed significantly sooner than with other systems by taking advantage of the unique opportunity offered through augmentation of the previously flown NASA SIR-C and the X-SAR.[3]

SRTM is a cooperative project of the National Aeronautics and Space Administration (NASA) and the National Imagery and Mapping Agency (NIMA) in the U.S.A., and the Deutches Zentrum für Luft und Raumfahrt (DLR) in Germany. The Italian Space Agency is cooperating with DLR by contributing flight hardware previously flown in 1994, and by participating in data processing.

This paper is organized as follows. First, we will briefly review SAR interferometry. This will be followed by a description of the SRTM flight system, and some early results.

SAR INTERFEROMETRY

SAR interferometers for the measurement of topography can be implemented in one of two ways. In the case of single-pass interferometry, the system is configured to measure the two images at the same time through two different antennas usually arranged one above the other. The physical separation of the antennas is referred to as the *baseline* of the interferometer. In the case of repeat-track interferometry, the two images are acquired by physically imaging the scene at two different times using two different viewing geometries.

Until the flight of SRTM, single pass interferometers have been implemented using only airborne SARs.[1,4,5,6] Most of the research has gone into understanding the various error sources and how to correct their effects during and after processing. As a first step, careful motion compensation must be performed to correct for the actual deviation of the aircraft platform from a straight trajectory.[7] After single-look processing, the images are carefully co-registered to maximize the correlation between the images. The so-called *interferogram* is formed by subtracting the phase in one image from that in the other on a pixel-by-pixel basis. In practice, this is implemented by multiplying the one complex image by the complex conjugate of the other, and estimating the phases of the resulting complex numbers.

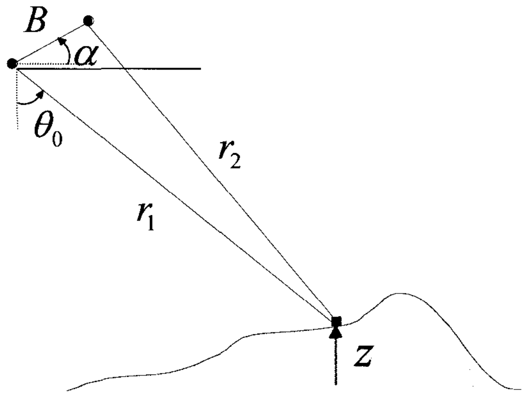

Figure 1. *A SAR interferometer uses two antennas at different positions to measure the difference in range to the surface.*

Interferometric radars measure the phase difference from two signals acquired through antennas at different elevation positions. In this section we assume that the SAR data from the two observations are mutually coherent, so that there is minimal phase noise in the data. It is easily shown, using the geometry in Figure 1, that the phase difference is

$$\Delta\phi = -\frac{a2\pi}{\lambda}(r_1 - r_2) \qquad (1)$$

where $a = 2$ for standard repeat-track interferometry, and $a = 1$ when the signal is transmitted out of one antenna and simultaneously received through two different antennas separated in elevation, such as in the case of SRTM. In this equation, λ is the radar wavelength, and r_1 and r_2 represent the radar ranges from each antenna to the point being observed. Using the law of cosines, and the assumption that the range to the surface is much larger than the interferometric baseline, it can be shown that this phase difference can be written in terms of the baseline separating the antennas, B, the radar look angle θ_0, and the angle of the baseline relative to the horizontal α:

$$\Delta\phi = -\frac{a2\pi}{\lambda} B\sin(\theta_0 - \alpha) \qquad (2)$$

In the presence of topography, the radar look angle is slightly modified from the value in the absence of surface relief. It can then be shown that if the phase field due to a smooth earth (no surface relief) is subtracted from the interferometric phase, the resulting "flattened" phase difference is

$$\Delta\phi_{flat} \approx -\frac{a2\pi}{\lambda} B\cos(\theta_0 - \alpha)\frac{z}{r_1 \sin\theta_0} \qquad (3)$$

where z is the elevation of the pixel above the flat earth reference. The interferometric ambiguity height is defined as that change in elevation for which the "flattened" phase changes by one cycle. This is easily shown from (3) to be

$$e = \frac{\lambda r_1 \sin\theta_0}{aB_\perp}, \qquad (4)$$

where $B_\perp = B\cos(\theta_0 - \alpha)$ is the component of the baseline perpendicular to the radar look direction. The value of the ambiguity height e is important, since the radar system only measures the phase modulo 2π. Therefore, if the total relief in the scene exceeds the ambiguity height, the phase will be "wrapped", and the interferogram will appear as a contour map. To reconstruct the topography, one will have to "unwrap" the phase. Indeed, this is the usual situation.

Once the images are processed and combined, the measured phase must be unwrapped. During this procedure, the observed phase, which can vary only between 0 and 2π, must be unwrapped to retrieve the original phase by adding or subtracting an estimate of the correct multiples of 2π. Phase unwrapping algorithms are based on the reconstruction of the original phase by integrating its gradient computed from the original wrapped phase values. The phase unwrapping problem is far from trivial because most SAR images of interest generate rapidly changing phase signals, and often phase discontinuities in the interferogram. For example, mountain peaks sensed by a satellite SAR may appear at shorter radar range than valley features that in fact are closer to the sensor's nadir. This phenomenon is denoted *layover* because of the appearance of the resulting image distortion. Of course, the corresponding phase signal may go through an abrupt phase jump of many multiples of 2π at the boundaries of such features.

The earliest phase unwrapping routine in the SAR interferometry context was published by Goldstein *et al.*[8] In this algorithm, which is based on the *local* integration of the phase gradient, areas are identified where the phase is discontinuous due to for example layover or poor signal-to-noise ratios (called residues). Those areas are then connected by branch cuts, and the phase unwrapping routine is implemented such that branch cuts are not crossed when unwrapping the phases.

Even after the phases have been unwrapped, the absolute phase is still not known. This absolute phase is required to produce a height map that is calibrated in the absolute sense. One way to estimate this absolute phase is to use ground control points with known elevations in the scene. However, this human intervention severely limits the ease with which interferometry can be used operationally. Madsen *et al.* reported a method by which the radar data itself can be used to estimate its absolute phase.[7] The radar bandwidth is split into its upper and lower halves. The method uses the differential interferogram (formed by subtracting the upper half spectrum interferogram from the lower half spectrum interferogram) to generate an equivalent low frequency interferometer to estimate the absolute phase.

THE SRTM FLIGHT SYSTEM

As mentioned in the previous Section, a radar interferometer images a scene from two slightly different positions. In the case of a single-pass interferometer, such as SRTM, these images are acquired simultaneously. This means that one needs to separate the antenna systems in space, but always know the relative positions of the antennas in order to reconstruct the topography correctly.

The SRTM payload used the maximum resources that the Space Shuttle could offer with respect to energy use, flight duration and payload mass, with the result that the mapping phase of the flight operations was limited to 159 orbits. With the 60-meter long mast, and the more than 13 tons of payload, SRTM was the largest structure ever flown in space.

The SRTM actually flew two interferometers, a C-band system provided by the U.S.A., and an X-band system provided by Germany. In both cases, the transmitter was located in the Shuttle cargo bay. The baseline of the interferometer was formed by a specially designed 60-meter long mast, which extended from the Shuttle cargo bay, and carried receive-only antennas on the other end.

A swath width of greater than approximately 218 km is required to cover the earth completely in 159 orbits. The existing SIR-C ScanSAR mode, combined with the dual-polarization capability, allowed a 225-km swath at C-band. This provided complete land coverage within 57 degrees north and south latitude. The X-band interferometer swath was limited to 45-50 km, as it was not capable of operating in the ScanSAR mode.

The baseline of the interferometer was formed by a specially designed 60-meter long mast. The mast is a carbon fiber truss structure that consisted of 87 cube-shaped sections, called bays. The entire mast was stored in a 3 m long canister, and small electrical motors were used to deploy and retract the mast prior to and after mapping operations. The mast was deployed and retracted by a specially designed rotating mechanism housed inside the canister. Unique latches on the diagonal members of the truss structure of the mast snapped into place and provided rigidity as the mast was deployed bay-by-bay out of the canister.

In order to reconstruct the topography accurately from the radar data, one needs to know the absolute length and orientation of the baseline, as well as the absolute position of the Shuttle. The Attitude and Orbit Determination Avionics (AODA) system combined the functions of metrology, attitude and orbit determination to provide this information. The attitude of the outboard antenna structure was measured using an array of three red light emitting diodes, whose relative positions were measured using the ASTROS target tracker. An Inertial Reference Unit (IRU) was used to measure changes in the attitude very precisely. Data from the IRU and a star tracker were combined to provide an absolute reference of the baseline attitude relative to known stars. The length of the baseline was measured using an Electronic Distance Measurement Unit mounted in the Shuttle cargo bay and a corner-cube reflector mounted on the outboard antenna structure. This system measured the length of the mast to an accuracy of 1 millimeter. Finally, the absolute position of the Shuttle was measured using global positioning satellite receivers with the antennas mounted on the outboard antenna structure to provide the best view of the GPS satellites.

The C-band SRTM system was designed to achieve a height accuracy better than 16 meters absolute and 11 meters relative, where these values are the 90% linear error after processing both ascending and descending passes. The elevation postings are 30 meters.

THE SRTM FLIGHT OPERATIONS

SRTM was launched on board the Space Shuttle Endeavour on February 11, 2000 at 17:43 GMT from the Kennedy Space Center as mission STS-99. Endeavour was placed on a 233 km orbit with an inclination of 57 degrees, the maximum possible with the SRTM payload mass and energy requirements.

The first 12 hours of the mission served as the On Orbit Checkout phase during which the payload bay doors were opened, the payload activated, and the mast extended. The inboard and outboard antennas were than aligned relative to each other before mapping operations could begin.

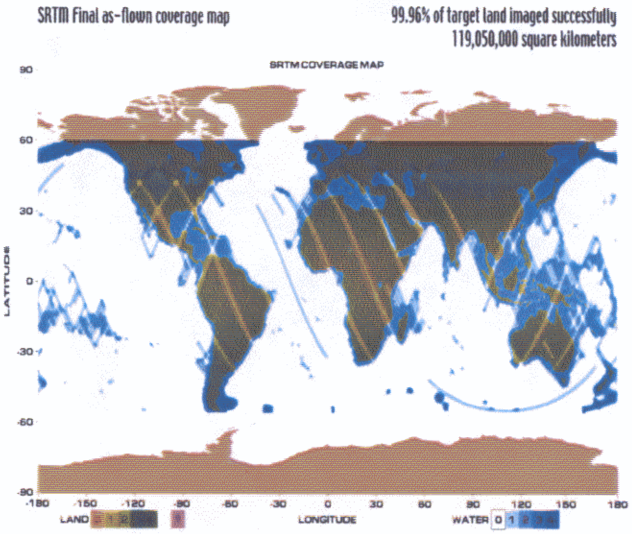

Figure 2. *SRTM C_band coverage during mission STS-99. A total of 119.51 million square kilometers were imaged.*

The checkout phase was followed by another 159 orbits of mapping operations during which the goal was to map all the land mass that could be viewed by the radars. During the mapping phase, seven special orbit maneuvers, known as "fly-cast" maneuvers, were used to raise the shuttle periodically to maintain the required orbit height.

Figure 2 shows the coverage of the C-band interferometer during the STS-99 mission. A total of 119.51 million square kilometers were imaged. Of the target land area, 99.97% was imaged at least once, and 94.6% was imaged at least twice. (The data from two separate passes must be combined in order to meet the height accuracy requirements.) High latitude sites were imaged many times, and 24% of the targeted land mass was imaged at least four times. The 8.6 Terabytes of C-band data were recorded on 208 high density digital data tapes and stored on the Shuttle.

After 11 days, 5 hours, and 58 minutes of a near perfect mission, the shuttle and its 6 crew members landed on February 22, 2000 at 23:22 GMT at the Kennedy Space Center.

EXAMPLE OF INITIAL RESULTS

The radar image shown in Figure 3 is the first to show the full 240-kilometer-wide (150 mile) swath collected by the Shuttle Radar Topography Mission (SRTM). The area shown is in the state of Bahia in Brazil. The semi-circular mountains along the left side of the image are the Serra Da Jacobin, which rise to 1100 meters (3600 feet) above sea level. The total relief shown is approximately 800 meters (2600 feet). The right part of the image is the Sertao, a semi-arid region, that is subject to severe droughts during El Nino events. A small portion of the Sao Francisco River, the longest river (1609 kilometers or 1000 miles) entirely within Brazil, cuts across the lower right corner of the image. This river is a major source of water for irrigation and hydroelectric power. Mapping such regions will allow scientists to better understand the relationships between flooding cycles, drought and human influences on ecosystems.

This image combines two types of data from the Shuttle Radar Topography Mission. The image brightness corresponds to the strength of the radar signal reflected from the ground, while colors show the elevation as measured by SRTM. The three dark horizontal stripes show the boundaries where four segments of the swath are merged to form the full scanned swath. These will be removed in later processing. Colors range from green at the lowest elevations to reddish at the highest elevations.

This shaded relief image shown in Figure 4 was generated using topographic data from the Shuttle Radar Topography Mission. A computer-generated artificial light source illuminates the elevation data to produce a pattern of light and shadows. Slopes facing the light appear bright, while those facing away are shaded. On flatter surfaces, the pattern of light and shadows can reveal subtle features in the terrain. Colors show the elevation as measured by SRTM. Colors range from green at the lowest elevations to reddish at the highest elevations. Shaded relief maps are commonly used in applications such as geologic mapping and land use planning.

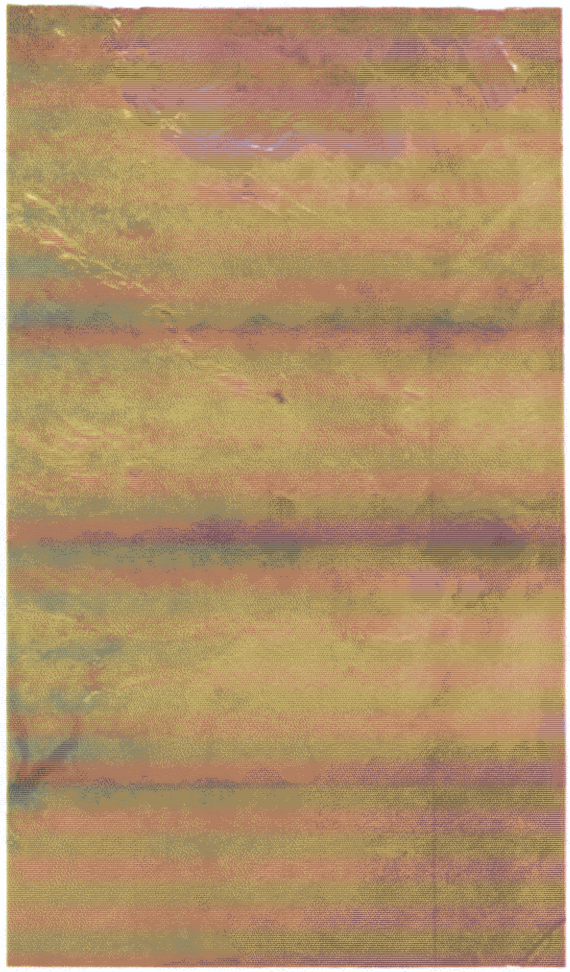

Figure 3. *SRTM image of the state of Bahia in Brazil. Brightness of the image is proportional to the radar cross-section. The image is 240 km from top to bottom. See text for more details.*

Figure 5 shows a three-dimensional perspective view, looking up the Tigil River, of the western side of the volcanically active Kamchatka Peninsula, Russia. The image shows that the Tigil River has eroded down from a higher and differing landscape and now flows through, rather than around the large green-colored bedrock ridge in the foreground. The older surface was likely composed of volcanic ash and debris from eruptions of nearby volcanoes. The green tones indicate that denser vegetation grows on south facing sunlit slopes at the northern latitudes. This image shows how data collected by the Shuttle Radar Topography Mission (SRTM) can be used to enhance other satellite images. Color and natural shading are provided by a Landsat 7 image acquired on January 31, 2000. Terrain perspective and shading were derived from SRTM elevation data acquired on February 12, 2000. Topography is exaggerated by about six times vertically. The United States Geological Survey's Earth Resources Observations Systems (EROS) Data Center, Sioux Falls, South Dakota, provided the Landsat data.

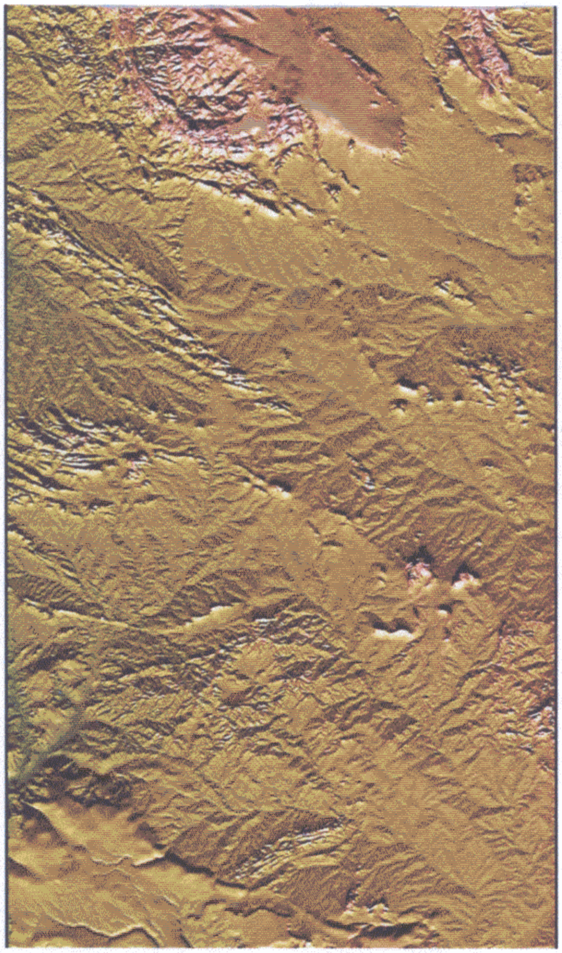

Figure 4. *Shaded relief image of the same area shown in Figure 3. Note the increase in information available about the terrain in this display as compared to the radar image data only as shown in Figure 3.*

Figure 5. *Overlay of Landsat data (color) on the totpogrpahy provided by the SRTM data of an area on the Kamchatka peninsula. See text for details.*

SUMMARY

This paper provides a description of the shuttle radar topography mission, with results of the coverage achieved. We also presented early results from the mission. Because the SRTM topography data are geocoded, it is easily combined with similar data from other sensors. It is also easily incorporated into geographical information systems.

ACKNOWLEDGMENT

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